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Public perception of carbon capture and storage (CCS): A review

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ABSTRACT

Carbon capture and storage (CCS) is regarded as an important bridging technology to a sustainable energy production. Whether it will be deployed on a large scale depends on both technological advances and social processes. Public perception of CCS can be crucial, and research interest in this topic has been growing. This review analyzes the public perception research thus far (42 articles were identified). Laypeople's concerns and spontaneous reactions to the technology have been thoroughly analyzed, and the results form a good basis for risk communication about CCS. What deserves more research is the role of the context (particularly the social context) in which CCS would be deployed. More case studies are also needed to gain a clearer picture of what matters for CCS acceptance at the project level, as opposed to societal acceptability of CCS.

Contents

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1. Introduction

Tackling climate change is a prominent and pressing problem today. Carbon dioxide (CO_2) emissions from the burning of fossil fuels are one of the major contributors to global warming, and they need to be reduced drastically to keep within the goal of a maximum of 2 °C warming. The energy sector remains one of the main sources of CO_2 emissions, and fossil fuels, particularly coal, are dominant in electricity production [1]. A technology that can help mitigate these emissions is carbon capture and storage (CCS). CO_2 is captured at large point sources, typically coal-fired power plants, transported to suitable storage locations and then injected into the deep subsurface. The goal is to permanently sequester the CO_2 in certain geological formations. This approach is not truly sustainable, because it relies on fossil fuels for energy production (although CCS with biomass is also possible), but it can avoid significant amounts of CO_2 emissions. According to the International Energy Agency's BLUE Map scenario, CCS could account for up to 19% of the global emission reductions by 2050 [2]. It could thus play a crucial role in smoothing the transition to truly sustainable energy production from renewable sources.

Whether CCS will actually be deployed on that large scale depends on the one hand on technological advances and on the other on social processes, such as energy policies and public perception. At least in democratic countries, the public generally has a say in whether large-scale technologies are adopted; if not at the more strategic national level, they can protest the implementation of specific projects. Therefore, it is important to understand how the public perceives such technologies, so that stakeholders can make decisions that are aligned with the public's views and avoid conflicts. Public perception of CCS has been a research topic for roughly a decade. Particularly in the last couple of years, there has been an increase in publications. We think it is useful to take a step back now and get a comprehensive picture of what we know so far. The aim of this review is to give an overview of empirical findings regarding public perception of CCS, identify areas where much research has been conducted and identify areas that are still under-researched. Ultimately, the goal is to inform better policy decisions with insights from public perception research.

First, we will present a framework of energy technology acceptance. The variables in this framework will be used to structure the results of our review. This is followed by a description of how the articles discussed in this review were found and selected. Section 4 gives a general overview of the publications that were included. Section 5 presents some key results for each element of the technology acceptance framework. We then give a brief summary of the results and point to possible avenues for future research. The paper concludes with practical implications for CCS implementation.

2. Acceptance of new energy technologies

New energy technologies often face skepticism or downright opposition by the public. Also in the case of renewable and sustainable energy technologies, acceptance is not guaranteed and depends on many factors [3]. Despite growing awareness and an increasing number of studies of public acceptance of different technologies, there is still no general psychological model to explain technology acceptance. Most studies focus only on selected factors and are therefore very hard to compare. Recently, Huijts et al. [4] tried to fill this gap by building a framework that pulls together different psychological theories and concepts that have been applied in acceptance research of sustainable energy technologies. It includes elements from the theory of planned behavior [5] (attitude, perceived behavioral control, social norms), from norm activation theory [6] and from theories of affect. These in turn are influenced by other variables, such as trust, fairness, perceived risks and benefits, or knowledge. An overview of the concepts can be found in Table 1. The exact causal relationships between those concepts have not yet been tested empirically. The framework constitutes a good starting point, however, to identify factors that are relevant for the acceptance of new energy technologies. We have therefore chosen to structure our review

Table 1
Concepts of the energy technology acceptance framework [4] as used in this article.

Concept	Definition
Acceptance/attitude	Both expressed acceptance ("I would accept CCS") and revealed acceptance (whether people engage in activities for or against CCS)
Knowledge	Awareness of CCS, self-assessed knowledge and objectively assessed knowledge
Experience	Direct experience with CCS, but also with related technologies (e.g., fossil fuel extraction, underground gas storage)
Trust	Trust in stakeholders. In the case of CCS typically project developers, government, NGOs
Fairness	Two types: Procedural fairness (fairness of decision processes) and distributive fairness (distribution of costs, risks, benefits)
Affect	Feelings towards CCS, with positive and negative affect being two distinct dimensions
Perceived costs	Financial costs for individuals and society, and psychological costs (e.g., effort)
Perceived risks	Potential risks to the health and safety of both humans and nature
Perceived benefits	All potential benefits attributed to CCS: for oneself, society and the environment
Outcome efficacy	Belief that one's own behavior affects the implementation of CCS
Problem perception	Awareness of climate change and consequences if no new technologies are implemented

article along those variables. All the variables discussed by Huijts et al. [4] apply to the case of CCS, with one exception: We exclude norms (both personal and social) from our discussion, because we do not think that this concept can be usefully applied in the CCS context. The technology is so young and so little known that no norms have been established yet regarding CCS. At the same time, we identified two additional concepts that seem relevant in the specific case of CCS, but that are not included in the framework; these will be discussed in Section 5.12. In the following, we give a brief overview of the different elements of the energy technology acceptance framework and their operationalization.

2.1. Acceptance and acceptability

Sometimes, a distinction is made between acceptance and acceptability. From a linguistic point of view, acceptance refers to the act of accepting, whereas acceptability is a property of the item to be accepted. Huijts et al. [4] draw a slightly different distinction: they define acceptance as behavior toward an energy technology, and acceptability as an attitude (i.e., an evaluative judgment) toward a new technology or toward possible behaviors regarding the technology. We find that in the case of CCS, it is unclear what behavior should be used as an indicator of acceptance (the act of not protesting, protesting as sign of non-acceptance, voting behavior, etc.). We find it more useful to use only the term acceptance, but in certain cases distinguish between expressed acceptance and revealed acceptance; we borrow this terminology from risk acceptance literature, which distinguishes between expressed preference and revealed preference regarding risks [7]. Expressed acceptance is the agreement with statements such as "I would accept a CCS project in my community," and revealed acceptance is the act of (non)engaging in activities to promote or prevent CCS. Using this broader definition of acceptance is more consistent with the terminology used in CCS public perception research. Most studies investigated what Huijts et al. [4] would call attitude, but the authors themselves call it acceptance.

2.2. Knowledge

Knowledge about a technology and how it functions undoubtedly influences how a person evaluates the technology in question. Knowledge can be operationalized differently: it can range from mere awareness that the technology exists to subjective knowledge (i.e., self-assessed knowledge) to objective knowledge (usually measured with true/false-type questions developed by experts). In this review, we will subsume all of the above under the concept knowledge.

2.3. Experience with the technology

Concrete experiences with a technology influence how people perceive it. In the case of CCS, only few people have direct experience with the technology. However, there are related technologies that are more common and that might also shape the perception of CCS, such as fossil fuel extraction or underground gas storage. We believe that they are relevant because they also use the deep subsurface and are related to energy production.

2.4. Trust

Trust in relevant stakeholders has been found to be a reliable predictor of the acceptance of new technologies. Because knowledge is low, people use their trust in promoters or opponents of technology as a heuristic for its acceptability. This relationship is often mediated through perceived risks and benefits [8,9].

2.5. Fairness

How fairly people perceive the way a technology is implemented can greatly affect their acceptance. A distinction can be made between procedural fairness, which relates to the decision processes, and distributive fairness, which refers to the distribution of costs, risks and benefits [4,10].

2.6. Affect

Feelings toward a technology, or affect, are also relevant for attitude formation [11]. Positive and negative affect can be conceptualized as two distinct factors, rather than two ends of one continuum [12].

2.7. Perceived costs

Costs refer to financial costs for the individual and society, but also psychological costs, such as effort.

2.8. Perceived risks

Perceived risks can be safety risks for humans and nature, but also financial risks according to Hujits et al. [4]. Because the conceptual difference between perceived costs and perceived financial risks is not very clear, we decided to use the term perceived risks for health and safety risks, and refer to perceived financial risks as perceived costs.

2.9. Perceived benefits

Perceived benefits encompass all potential benefits the public sees in a technology. This includes personal and societal benefits, but also benefits for the environment.

2.10. Outcome efficacy/perceived behavioral control

There are two different types of outcome efficacy according to Huijts et al. [4]: the belief that the new technology will actually reduce energy problems, and the belief that one's own behavior will impact the implementation of the technology. In the case of CCS, the first kind is almost indistinguishable from benefit perception. Therefore, we use the term outcome efficacy only for the second type – perceived influence on technology implementation. This in turn is very similar to perceived behavioral control, which constitutes a separate factor in the framework by Huijts et al. [13], but is not discussed separately in this review.

2.11. Problem perception

Problem perception is the "awareness of problems related to the current energy system when no new energy technology is implemented and used" [4]. This includes climate change, which is very relevant in the case of CCS.

3. Selection of studies

A literature search was conducted on Web of Science in December 2012. We searched for CCS (search terms "CCS," "carbon capture," "CO_2 storage") in combination with each of the following terms: "acceptance," "acceptability," "perception," "attitude," "public opinion." Conference proceedings were excluded from the search. The following criteria were applied to select an article: (a) it dealt with public perception rather than stakeholder perception, and (b) it reported empirical findings and was not purely theory-based, or a commentary.

The search was supplemented by snowballing to identify additional studies. Through this, we identified 45 papers. After reviewing them in greater detail, we decided to exclude two media analyses, because they did not directly assess public opinion. It is reasonable to argue that media coverage is a useful proxy for public perception, but this was not the focus of our review. One more publication was excluded because it was about public perception of oceanic carbon sequestration as opposed to geological sequestration. Oceanic disposal is no longer considered a viable option for CCS, and it might be perceived differently from geological sequestration [14], which was the (primary) focus of the remaining studies. A total of 42 empirical research articles was therefore included, which will be discussed in the following sections.

4. Overview of the studies

The earliest article included was published in 2002 [15], which shows how young the field of public perception research of CCS is. There has been an increase in studies over the last years, and 24 articles were published between 2010 and 2012. Where studies on public perception of CCS were conducted does not necessarily map to where CCS activities actually take place, as can be seen in Table 2. Table 2 compares the CO_2 emissions of countries with the number of CCS projects and the number of public perception studies conducted there. The list includes only countries with at least one public perception study. Two continents are completely absent: South America and Africa. South America currently has no CCS activities, and Africa has only the In Salah storage project.

In terms of methodology, the studies in this review covered quite a wide range. A third ($n=14$) were qualitative. They used interviews, focus groups and workshops. The remaining studies ($n=28$) can be classified as quantitative. They differed in their data collection (paper–pencil surveys, online surveys, interviews, laboratory experiments) and data analysis (frequencies, conjoint analysis, regression, structural equation modeling, analysis of variance). They were heterogeneous in their research questions and the variables measured. A detailed overview of the studies, where they were conducted, their research methods and key findings can be found in Tables A1 and A2 in Appendix A.

Table 2
Countries where CCS studies were conducted, their CO_2 emissions and number of CCS projects.

Country	Emissions[a]	CCS projects[b]	Studies
China	7711	11	1
US	5415	23	7
Japan	1168	0	3
Germany	770	0	3
UK	493	6	4
Canada	488	8	2
Australia	380	4	5
France	361	1	1
Poland	316	1	1
Spain	267	1	4
Netherlands	191	2	14
Belgium	115	0	1
Sweden	52	0	1
Switzerland	41	0	7

Note: The number of studies does not add up to the number of articles considered in this review, because some articles report on studies conducted in multiple countries.

[a] CO_2 emissions (in million tons) in 2010 (IEA, Paris, 2012).
[b] Large scale integrated projects (The Global CCS Institute, 2013, 2013).

5. Key results

In the following, we give an overview of the most important findings that can be derived from the studies. The results are structured along the variables of the technology acceptance framework discussed in Section 2 [4]. Tables 3 and 4 summarize which study included which concept(s).

5.1. Attitude and acceptance

Most studies measured expressed acceptance. There are not many CCS projects yet where revealed acceptance could be measured, and many studies were conducted in places where CCS has not been implemented yet, but where there is interest in gauging public opinion beforehand. Therefore, it is difficult to interpret and compare levels of reported acceptance. Because CCS is little known, participants had to be given information about the technology, and their opinion is likely to be highly sensitive to the content of that information and to the research context. In our discussion of the results, we will therefore focus on studies that investigated which variables influence attitude, rather than reporting absolute levels of attitude. Studies that do measure absolute acceptance typically find means that are close to the midpoint of the scale; few people take an extreme stance on CCS, neither positively nor negatively. The technology is rarely categorically rejected, because people see the need for reducing CO_2 emissions into the atmosphere. At the same time, they object to the fact that it is an "end-of-pipe" solution, which does not reduce the production of CO_2 from fossil fuels, and they want to see it embedded in a comprehensive energy strategy that addresses the problem of climate change from multiple angles. Overall, it could be said that CCS is reluctantly accepted.

Many studies confirmed the typical finding that risk and benefit perceptions are two of the main predictors of the acceptance of a technology [16–20]. Duan et al. [21] measured perceived benefits but not perceived risks, and it was the most influential predictor in their regression. Trust in stakeholders is another influential variable that can have direct effects on acceptance, or through perceived risks and benefits [17–20]. Studies that included none of these variables had low explained variance, although they found some significant other factors. De Best-Waldhober et al. [22], for example, concluded that their participants based their evaluations to some extent on the aspects and

Table 3
Overview of concepts investigated in qualitative studies.

Study	Ex.	Kn.	Tr.	PF	DF	PA	NA	PC	PR	PB	OE	PP	Ac.
Anderson et al. [24]	✓			✓					✓		✓		✓
Ashworth et al. [25]			✓							✓			✓
Ashworth et al. [46]		✓							✓	✓		✓	✓
Fleishman et al. [31]		✓											✓
L'Orange Seigo et al. [47]		✓							✓	✓			
Gough et al. [15]			✓					✓	✓			✓	✓
Oltra et al. [41]		✓	✓						✓			✓	✓
Oltra et al. [26]	✓		✓		✓			✓	✓	✓			✓
Palmgren et al. [14]								✓	✓			✓	✓
Shackley et al. [48]									✓	✓		✓	✓
Upham and Roberts [27]	✓		✓					✓	✓			✓	✓
Wallquist et al. [51]		✓							✓	✓		✓	
Wong-Parodi and Ray [28]	✓		✓	✓					✓	✓	✓	✓	✓
Wong-Parodi et al. [29]	✓					✓	✓		✓	✓			

Ex.=Experience, Kn.=Knowledge, Tr.=Trust, PF=Procedural fairness, DF=Distributive fairness, PA=Positive affect, NA=Negative affect, PC=Perceived costs, PR=perceived risks, PB=Perceived benefits, OE=Outcome efficacy, PP=Problem perception, Ac.=Acceptance.

Table 4
Overview of concepts investigated in quantitative studies.

Study	Ex.	Kn.	Tr.	PF	DF	PA	NA	PC	PR	PB	OE	PP	Ac.
Carley et al. [52]		✓										✓	✓
de Best-Waldhober et al. [30]		✓											✓
de Best-Waldhober et al. [32]		✓										✓	✓
de Best-Waldhober et al. [22]		✓											✓
Duan [21]		✓							✓	✓		✓	✓
Ha-Duong et al. [53]		✓							✓			✓	✓
Huijts et al. [13]		✓	✓			✓	✓		✓	✓			✓
Kraeusel and Möst [16]		✓						✓	✓	✓		✓	✓
L'Orange Seigo et al. [33]		✓					✓		✓	✓			✓
Midden and Huijts [37]			✓			✓	✓		✓	✓			✓
Miller et al. [39]		✓	✓									✓	✓
Miller et al. [38]		✓	✓									✓	✓
Moutenet et al. [34]		✓										✓	✓
Oltra et al. [35]		✓							✓				✓
Palmgren et al. [14]									✓	✓		✓	✓
Reiner et al. [54]		✓										✓	✓
Sharp et al. [23]		✓							✓			✓	✓
ter Mors et al. [40]			✓										
Terwel et al. [18]			✓						✓	✓			✓
Terwel et al. [42]			✓										
Terwel et al. [43]			✓	✓									
Terwel and Daamen [17]			✓						✓	✓			✓
Terwel et al. [44]			✓	✓					✓		✓	✓	✓
Tokushige et al. [49]		✓							✓	✓			✓
Tokushige et al. [19]		✓	✓						✓	✓		✓	✓
Wallquist et al. [56]													✓
Wallquist et al. [50]		✓							✓	✓			
Wallquist et al. [20]			✓						✓	✓			✓
Wallquist et al. [36]		✓							✓	✓		✓	

Ex.=Experience, Kn.=Knowledge, Tr.=Trust, PF=Procedural fairness, DF=Distributive fairness, PA=Positive affect, NA=Negative affect, PC=Perceived costs, PR=perceived risks, PB=Perceived benefits, OE=Outcome efficacy, PP=Problem perception, Ac.=Acceptance.

consequences of the technologies explained, but that there are clearly other, more influential factors. Sharp et al. [23] found that media reports and the extent to which CCS is used in other countries significantly influenced support for CCS. It is also possible to influence attitude toward CCS by giving specific information (see Section 5.3 on Knowledge).

Only three case studies measured revealed acceptance as opposed to expressed acceptance. Anderson et al. [24] emphasized the importance of participation, which should live up to certain standards. For project managers, it is important to know a community's social characteristics and to be sure that they might not be mistaking for acceptance what is actually passive resignation. Ashworth et al. [25] formulated five success factors for projects that go in a similar direction. The social context of a site should be considered, and the project should be flexible enough to adjust to it; communication experts should be an integral part of the project from the beginning, and important stakeholders need to be aligned. Oltra et al. [26] saw three issues as most important for acceptance: trust in the developer, the quality of public engagement activities, and the public's and stakeholders' perceptions of the need for the facility.

5.2. *Experience*

Only five articles discussed the role of experience for acceptance of CCS [24,26–29]. It is interesting that they were all qualitative studies, and three were case studies. Anderson et al. [24] discussed farmers' acceptance of the Otway project in Australia. They cited experience with the gas industry as a key factor for initial acceptance. The farmers were familiar with pipelines and gas wells, and appreciated the extra income they received from compensation payments. Later on in the project, however, there were negative experiences with the CCS activities, which caused ongoing interruption to farm management activities. As a consequence, old concerns about the gas industry emerged again, and acceptance dropped. Oltra et al. [26] also found a relationship between previous experience with the fossil fuel industry and acceptance of CCS projects in their analysis of five European cases. The two projects that did not face strong opposition were located in communities with prior experience.

Wong-Parodi and Ray [28] looked at two communities in California that might have been host sites for a CSS project. Both had previous experience with industrial harm and how it was handled. One community had been able to stop the construction of a chemical plant near a river, which strengthened their sense of empowerment; they felt that they would also be able to exercise their voice in the case of a CCS project, if anything went wrong. The other community, however, had an unresolved water contamination issue; they felt that if anything went wrong with the proposed CCS facility, their complaints would go unheard. This feeling of helplessness would likely have prevented them from actively protesting against the CCS project; it is important to note, however, that this would not have been due to real acceptance.

Upham and Roberts [27] conducted focus groups, and their participants used their experience with natural gas storage and transport as a proxy for assessing the safety of the transport and storage aspects of CCS.

5.3. *Knowledge*

Numerous studies assessed whether the general public had heard of CCS and knew what it is used for. Awareness is generally quite low, and only a small minority had heard of the technology. De Best-Waldober et al. [22,30] and Fleishman et al. [31] assessed how thoroughly informed participants evaluate CCS. The researchers gave participants rather extensive background information on climate change, energy production technologies and how CCS functions. This avoided the problem that people might report only pseudo-opinions because they are unfamiliar with CCS. Informed participants were neither overly enthusiastic about CCS nor entirely opposed to it. De Best-Waldhober et al. found that aspects and consequences of the technology itself left much of the variance in people's evaluations unexplained. There must be other factors that influence judgments about CCS. This finding was replicated in a more recent study by de Best-Waldhober et al. [32], which found only a weak relationship between knowledge of CO_2 and CCS, and attitude toward CCS.

L'Orange Seigo et al. [33], Moutenet et al. [34], Oltra et al. [35] and Tokushige et al. [19] gave their respondents information about specific aspects of CCS and measured how that influenced attitude. L'Orange Seigo et al. [33] found that information about monitoring measures undertaken at CO_2 storage sites had an alarming rather than a reassuring effect, at least in men. Moutenet et al. [34] observed lower support for CCS, after participants were presented with the unfavorable views certain nongovernmental organizations (NGOs) hold of CCS. This relationship was likely mediated through trust, although this was not measured in the study. Oltra et al. [35] found a positive effect for information about the natural character of CO_2, although other manipulations in the study were unsuccessful at influencing attitudes. Similarly, Tokushige et al. [19] measured increased acceptance after their participants had read about natural analogues of CO_2 storage. Information about field demonstrations, however, barely influenced acceptance.

Only two studies [32,36] assessed objective knowledge of CCS. Knowledge was generally low, and typical misconceptions widespread. Such misconceptions are that the CO_2 is stored as a gas in large cavernous spaces, and that the applied pressure might lead to explosions. Wallquist et al. [36] found an effect of knowledge on risk and benefit perceptions, but the influence was rather limited.

5.4. Trust

Trust is recognized as a key variable for technology acceptance, and 18 of the studies we reviewed included it in some way in their analysis [13,15,17–20,25–27,29,37–44]. The most trusted stakeholders are researchers and NGOs. Two case studies by Ashworth et al. [25] and Oltra et al. [26] found accordingly that the projects that could be successfully implemented and faced the least opposition were research projects. Those run by energy companies, however, often faced strong opposition or were even cancelled. Industry is one of the least trusted stakeholders. Government organizations tend to fare better but are often not trusted to manage CCS operations safely.

Quantitative studies have found that the effect of trust on acceptance is not direct, but is mediated through perceived risks and perceived benefits [17–19]. Wallquist et al. [20] found an effect on perceived benefits, but not risks. And Midden et al. [37] further observed that the relationship between trust and perceived risks operated through affect.

The question is, of course, how trust comes about in the first place. Huijts et al. [13] found that trust in a stakeholder was influenced by the perceived similarity with that stakeholder, which is in accordance with the wider literature on trust [45,9]. Using experiments, Terwel et al. [43] examined the effects that group voice in decision making has on trust. Authorities were judged as more trustworthy if they granted different interest groups a voice in the decision-making process about CCS implementation, which in turn led to higher acceptance of the final decision. Knowledge had a moderating effect: Informed people cared more about group voice, whereas uninformed people were indifferent. Another study by Terwel et al. [42] investigated the relationship between corporate communications and trust. It was not just message content that was predictive of trust, but whether the message was in line with the assumed motives of the organization standing behind the communication. Industrial organizations, for example, were thought to act more out of self-serving motives than public interest. When they highlighted environmental benefits of CCS, trust was low, due to perceived dishonesty. Trust could be preserved, however, when an honest argument (financial interest) was coupled with a more public-serving message (CCS is good for the environment).

Ter Mors et al. [40] looked at when information from stakeholders is seen as trustworthy and reliable. Information coming from dissimilar but collaborating stakeholders was seen as more balanced and therefore trustworthy than information coming from one stakeholder alone. Trusted stakeholders were not negatively affected by collaborating with a less trusted stakeholder.

5.5. Fairness

The role of fairness (both distributive and procedural) has not been studied much in the context of CCS. Some studies touch the topic indirectly, and only two publications by Terwel et al. [43,44] address the role of fairness explicitly. The first is the same study that was discussed in the subsection on trust. Procedures that are perceived as fair lead to more trust and ultimately to higher acceptance. The second one is an analysis of the Barendrecht case (a project in the Netherlands that was cancelled, at least partially due to public resistance); local residents there found the decision-making procedure unfair and thought that Shell (the project developer) had undue influence, whereas local residents lacked decision power. Oltra et al. [26] also analyzed the Barendrecht case and observed that opposition was partially driven by local stakeholders questioning the need to select their community and not others as a storage site, particularly because they had already absorbed many infrastructure projects in previous years. This is clearly a concern with distributive fairness.

Wong-Parodi and Ray [28] stressed the importance of the empowerment of a community. This "partly stems from the community's ability to exercise voice and have recourse to compensation or damage mitigation" [28], which are aspects of procedural fairness. Anderson et al. [24] take a more normative stance: public participation should be an integral part of any CCS project, and a good participation process needs to ensure that the local population has appropriate resources, also in terms of social capital, to voice their needs and have their concerns addressed.

5.6. Affect

Affect is another variable that has received very little research attention. Midden and Huijts [37] included affect in their study and confirmed the finding that negative and positive affects are two separate dimensions, rather than two ends of a continuum. Both positive and negative affects were influenced by trust in their sample, and in turn influenced perceived benefits and risks. Huijts et al. [13] reported frequencies regarding affect; ratings of negative affect were higher in their sample than ratings of positive affect. In a study by L'Orange Seigo et al. [33], information on CO_2 monitoring measures induced higher levels of negative affect compared to a control group who did not receive the same information.

Wong-Parodi et al. [29] argued that pro-or anti-CCS messages are most persuasive if they trigger an emotional reaction. The authors called such messages "emotionally self-referent" (ESR). Participants in the study identified their own ESR triggers and used them to create messages in favor of or against CCS in their community. These messages were based on different arguments than those created by experts, and they were seen as more persuasive, although the participants believed the expert messages in terms of factual content.

5.7. Perceived costs

It is not always easy to distinguish perceived costs from perceived risks. Particularly in the case of CCS, cost estimates are associated with large uncertainties and might also be framed as financial risks. A few studies explicitly mention costs, however, in particular monetary costs. A number of participants in qualitative studies brought this issue up. In focus groups conducted by Upham and Roberts [27], costs were seen as a, if not the, major disadvantage by participants from the United Kingdom (UK), Germany and Poland. They thought that increased costs for electricity production should be shouldered by power companies rather than the consumer. Similar concerns were found by Gough et al. [15] and Palmgren et al. [14]. In the case studies discussed by Oltra et al. [26], a potential increase in electricity prices was one of the concerns raised in Bełchatów – a project faced with some opposition.

Kraeusel and Möst [16] conducted a conjoint study and included a monthly price premium as one of the factors. Participants were willing to pay a premium for an increased share of renewable energy in the electricity mix, but not for CCS.

5.8. Perceived risks

The majority of studies ($n=26$) investigate risk in some way [13–21,23,24,26–29,33,35–37,46,50,51]. Qualitative studies can

give insights into which kind of risks people are concerned about. By far the most frequently voiced concern is that the CO_2 might leak back into the atmosphere. This would at the same time undermine the single largest benefit of CCS. Concerns also exist about how such a leak might happen. Some people believe there might be sudden blowouts or explosions (both at the surface level, for example at injection wells, and underground). Another common concern is that ground movements might compromise the storage integrity. Multiple studies cite “earthquakes” as a potential risk, but it is not always clear whether it is meant that earthquakes would cause faults in the caprock and thus lead to leakage, or whether the pressure of the injected CO_2 might lead to earthquakes. CO_2 is also seen as a pollutant or a toxic substance, and people therefore feel uncomfortable disposing of it underground. They fear negative effects on ecosystems, although they cannot specify what these effects would be.

The second big set of potential risks voiced by laypeople revolves around the unsustainable nature of CCS: it does not tackle the root of the problem – producing CO_2 by burning fossil fuels – and is perceived as an end-of-pipe solution or sweeping the issue under the rug. There are also concerns that the development of CCS might reduce investments in renewable energy technologies. We call this set of concerns sustainability concerns.

A concern that was mentioned only in case studies was the potential impact on property values or tourism. This indicates that different risks can become focal once a specific project site has been selected.

When these concerns are measured quantitatively, it seems that sustainability concerns, fears of leakage and fear of overpressurization are most influential for risk perception as a whole [36]. Various studies looked at whether information about different aspects of CCS technology or CO_2 can influence risk perceptions [35,33,49,50], with mixed results. It seems possible to influence risk perception, but the effect is rather small, and different kinds of information have different effects.

Consistent with the risk perception literature in other domains, trust in stakeholders was found to be inversely related to risk perceptions [17–19]. Similarly, Midden and Huijts [37] found an impact of both negative and positive affect; negative affect increases risk perception, whereas positive affect decreases risk perception.

Also in agreement with the literature on risk perception and technology acceptance, a number of studies found that risk perceptions of CCS were a significant negative predictor of acceptance [16–21,37,44,49]. Wallquist et al. [20] found a particularly strong relationship between perceived risks and acceptance. They measured the latter as protest potential, in order to be closer to actual behavior.

5.9. Perceived benefits

Almost half the articles included benefit perception as their dependent or independent variable [13,16–21,26,28,29,33,36,37,41,46–50]. Interestingly, not all studies that tried to identify perceived risks also asked about perceived benefits, although perceived benefits are very important for acceptance, often even more relevant than perceived risks. This has also been found in the case of CCS [16–20,37,49].

The obvious benefit of CCS is its contribution to reducing CO_2 emissions and thus mitigating climate change. Sometimes this is framed as CCS allowing the continued use of fossil fuels, while still reducing CO_2 emissions. It thus enables a smoother transition to sustainable energy production. It could be argued that this is the only reason for and thus the only benefit of CCS. At a societal level, this might be true. But at the local level, there can be additional benefits, which were brought up by respondents in case studies or potential host communities [46,26,28,29]. They focused on economic benefits, which might come through job creation, tourism or future investment in the community. Ashworth et al. [25] also pointed to the importance of identifying local benefits in order to make a concrete CCS project successful.

At the broader, societal level, benefit perceptions seem to be positively influenced by trust [37,17–20] and positive affect [37]. L'Orange Seigo et al. [33] and Wallquist et al. [50] looked at how information can impact benefit perceptions. As in the case of risk perceptions, the effect depends on the exact type of information. Wallquist et al. [36] found that the most influential factor on benefit perception was sustainability concerns – higher concerns were associated with lower benefit perception. This factor was more important than actual factual knowledge about how CO_2 storage works.

5.10. Outcome efficacy

Outcome efficacy, or the belief that personal actions can actually influence the implementation of CCS technology, was explicitly addressed in only two studies. Anderson et al. [24] showed how a lack of social capital led to a sort of passive acceptance by farmers, which was less driven by favorable views of the CCS project than by insufficient social resources to make themselves heard. Social capital was defined as connections and networks between individuals, and the corresponding trust. Wong-Parodi et al. [28] looked at how a community's social economic standing and local history can affect their sense of empowerment. They compared a low-income, mostly Hispanic, community with a wealthier, mostly Caucasian, community in California. They found that the poorer community felt fairly powerless and did not believe that they would have much say in the siting process or that they would receive compensation if anything went wrong. Here also, the authors pointed out how this passive resignation should not be confused with acceptance.

Outcome efficacy is also related to perceived fairness. As Terwel et al. [44] showed, local residents in Barendrecht thought they did not have enough influence over the proposed CCS project, which led to low perceived fairness.

5.11. Problem perception

Problem perception was included in many studies we reviewed [14–16,19,21,23,27,32,34,36,38,39,41,44,48,51–54]. This is not surprising, given that mitigating climate change is the primary benefit of CCS. It would be hard to argue in favor of CCS, if the basic tenet that climate change is real and needs mitigating is not accepted. There seems to be general agreement among the public that climate change is happening and that action is necessary to reduce greenhouse gas emissions. The highest number of climate change deniers was reported by Reiner et al. [54] for the United States (US), where 7% of respondents indicated that global warming was not a problem. In the UK and Sweden, the same statement was endorsed by 3% and 2%, respectively.

Few studies looked at how awareness of climate change actually affects perception of CCS. Kreausel and Möst [16] found that people with higher climate change concern also had higher risk perceptions (which in turn would be expected to lead to lower acceptance). Contrary to that, Wallquist et al. [36] found a negative influence of climate change awareness on risk perception, and a positive influence on benefit perceptions. Similarly, Oltra et al. [41] reported that groups that accepted CCS thought that climate change was an urgent problem. Tokushige et al. [19] also looked

at the influence of problem perception on risk and benefit perceptions. They operationalized the concept slightly differently from other studies, however, and emphasized the aspect of human interference with nature and going against nature's laws. They found a positive influence on risk and benefit perceptions.

5.12. Other variables

A couple of concepts emerged as important variables for people's evaluation of CCS, but are not covered in the technology acceptance framework [4]. We will discuss them in the following.

5.12.1. Energy context

The current energy mix of a country where CCS is to be deployed and the available alternatives both seem to be very important to people. Within the technology acceptance framework, it could be argued that this acts through benefit perception, or it could be framed as a specific kind of risk. But because these concerns seem so prevalent in the case of CCS and have such large importance, we feel they deserve their own discussion. Several qualitative studies bring up this issue, which is closely related to the sustainability concerns mentioned above (see Section 5.8). Gough et al.'s [15] participants were concerned about investing in a technology that would be rendered obsolete by other low-carbon technologies. This could simply be framed as financial risks, but it also points to the fact that people do not evaluate CCS in isolation, but consider the availability of other technologies that might yield equal benefits. The same was found by Palmgren et al. [14], who stated that “many respondents indicated a desire to consider carbon capture and sequestration in the context of a broader set of options for carbon management.” Similarly, Shackley et al. [48] argued that results from their focus groups “strongly support[s] the need to embed CCS within a portfolio of decarbonization options and to promote CCS as a ‘bridging strategy’ to other lower zero-carbon energy sources.” Oltra et al. [41] found that rejection of CCS among participants was partially based on a preference for other renewable technologies.

Fleishman et al. [31] studied perceptions of CCS when it was embedded in realistic energy portfolios, rather than looking at the technology in isolation. Their results showed a more favorable evaluation of CCS than other studies. A study that tried to quantify the effects of framing CCS as a bridging technology was conducted by Wallquist et al. [50]. They gave participants in a within-subject experiment different types of information and measured the effect on risk and benefit perceptions. After participants read a paragraph on how CCS is only part of a solution and should be embedded in a range of other low-carbon technologies, their benefit perceptions increased and risk perceptions decreased.

5.12.2. Values

One particular set of values has emerged as an important predictor in some studies; it revolves around interference with nature. Gough et al. [15] highlighted two implicit cognitive models that participants seemed to hold regarding CCS, one of which is the belief that there is a web of interconnected ecosystems that can easily be disturbed, and interference in one place will cause disastrous chain reactions. Tokushige et al. [19] and Wallquist et al. [20] included interference with nature in structural equation models to predict acceptance. One called it “perception of interference with the environment for implementation of the geological storage of CO_2” and the other “tampering with the subsurface,” which is more specifically about the subsurface rather than nature in general. Tokushige et al. [19] found a significant impact on risk perception and a direct path to public acceptance. In Wallquist et al. [20], tampering with the subsurface was the single best predictor of perceived benefits and perceived risks. The finding that perceived interference with nature affects risk perceptions is in line with risk perception research in other energy-related domains [55].

Wallquist et al. [56] also conducted a conjoint study that looked at the relative impact of each of the three CCS elements (capture/CO_2 source, transport and storage) on overall acceptance of CCS. The factor CO2 source had two levels: CO_2 from a gas-fired power plant and CO_2 from a biogas-fired power plant. When the source of the CO_2 was biogas, there was no Not In My Backyard (NIMBY) effect, and participants did not seem to mind living near a storage site. This might seem irrational, because the CO_2 is the same, regardless of its origin. It is possible, however, that biogas is perceived as more natural, and therefore, CO_2 coming from it is regarded as less harmful than CO_2 from fossil fuels. This effect might have been particularly pronounced, because the study was conducted in German, and the prefix “bio-” has the meaning of “organic.”

These results point to a potentially important role of the value interference with nature regarding public perception of CCS. Further studies could try to clarify what the public perceives as (non)interference with nature, and what its exact role in acceptance of CCS is.

6. Summary and outlook

Over the last decade, a diverse body of articles has been published on public perception of CCS. As we have shown, the technology acceptance framework by Huijts et al. [4] is a useful tool for structuring the various results. Table 5 summarizes the most important findings for each variable in the framework, and the two additional variables we propose for the CCS case.

Aspects that have been well researched are the public's intuitive reaction to CCS, their mental models of the technology and the subsurface, and their awareness of climate change. These variables would be subsumed under knowledge in the technology acceptance framework. Although people generally know that climate change is happening, they are unsure what exactly is causing it or what possible mitigation options are. Many seem to underestimate the extent of emission reduction that is necessary, while overestimating how much can currently be achieved through the use of renewables. There are some small differences between countries, but overall, the mental models the general public holds of CCS and how it works are very similar.

What we know about these mental models is enough to draft risk communication that should be understandable and useful. Such communications are necessary to make sure the public has access to adequate information and can participate in democratic processes around the deployment of CCS. One should not expect, however, that risk communication can produce acceptance, or that information is the most influential variable for acceptance. Knowledge has been shown to have an impact on public attitude, but other variables are more important.

The best predictor of acceptance of CCS is benefit perceptions. This is typical for acceptance of new technologies [8,57]. In the case of CCS, benefit is intrinsically linked to the continued use of fossil fuels for electricity production. At least at the societal level, it is difficult to identify additional benefits to reducing CO_2 emissions. This could be the reason people feel a strong need to view CCS in context. They want to know about other alternatives, and are concerned about the unsustainable nature of the technology. CCS is seen as an end-of-pipe solution that might even displace

Table 5
Main findings for each concept.

Concept	Main findings
Acceptance	• Most important predictors are perceived risks, perceived benefits and trust • Aspects and consequences of technology itself play a role, but the influence is limited • Social context of project site is influential
Experience	• Case studies point to the importance of prior experience with the fossil fuel or other industries for acceptance • Little research, worth exploring more
Knowledge	• The public's mental models and misconceptions about CCS are understood well enough to produce meaningful information materials • Pre-existing knowledge and information about CCS influence acceptance, but the impact is limited
Trust	• Important predictor of acceptance • Most trusted are researchers and NGOs, least trusted are industry stakeholders • Trust can be enhanced through fair procedures, honest communications and collaboration of multiple stakeholders
Fairness	• Case studies point to the importance of both procedural and distributive fairness • Little research, worth exploring more
Affect	• Positive and negative affect are two different dimensions • Affectively loaded messages are more persuasive; their content might be different from expert messages
Perceived costs	• Costs are seen as a major disadvantage of CCS
Perceived risks	• Potential risks that the public sees are quite well understood • Most important perceived risks are leakage and sustainability concerns • Perceived risks are one of the best predictors of acceptance
Perceived benefits	• Single best predictor for acceptance • Perceived benefits are influenced by trust • Important for concrete projects to identify local benefits
Outcome efficacy	• Low perceived outcome efficacy prevents protest, even if acceptance is low
Problem perception	• General agreement that climate change is real, only small portion of deniers • Tends to have positive effect on benefit perception, negative effect on risk perception
Energy context	• People want to discuss CCS within broader context of alternatives • Evaluation in context tends to be more positive than in isolation
Interference with nature	• Seems to be important predictor for risk perception, benefit perception and acceptance • More research needed to clarify role

investment in renewable energy technologies. Such sustainability concerns are among the most important risks people see regarding CCS. Other relevant risks are leakage or overpressurization of the CO_2 storage formation.

These last concerns are real and quite prevalent. At the same time, they do not seem to scare people to the extreme. When perceived risks are assessed quantitatively, the mean scores are typically just above the midpoint of the scale, and almost nobody uses the scale extremes. This is consistent with the finding by Tokushige et al. [49] that CCS loads not overly high on the “dread” factor within the psychometric paradigm [7]. At the societal level, perceived risks should not be a major barrier to CCS implementation. At the local level, however, the picture might look different. People who actively protest CCS sites can be motivated by perceived risks, and local protest can cause a project to be cancelled [25,26,44]. At the same time, absence of protest does not necessarily mean that the local population is happy with the proposed CCS project. They might simply feel that their voice would not be heard anyway. More case studies would be useful to further refine our knowledge of what the key factors are for the success or failure of a project, and how these factors might differ from those that are crucial for acceptance at the societal level.

To date, many studies have focused on how properties of CCS itself affect acceptance. Newer research, however, points to the importance of context for the acceptance of CCS. At the local project level, the social context of the community plays a large role. We know it is important to take the history and social structure of a community into account – have there been activities of the fossil fuel industry in the past and does it form an integral part of the economy, how empowered do the residents feel, etc. Such questions are important, but it is not overly well understood in which ways exactly they contribute to local acceptance of a project, and how knowledge about the local context can be used to foster support or opposition to a project.

Fairness is another variable that is not specifically related to CCS but plays an important role in acceptance. Some studies point to the importance of perceived fairness regarding CCS (see Section 5.5). They emphasize the role of procedural fairness. There is room for more research, however, to better understand when a procedure is perceived as fair, and whether fairness is more important at the local level or equally important for societal acceptance. Research about other energy technologies indicates that the latter might be the case (e.g., [58]). Almost entirely neglected so far has been distributive fairness. Because CO_2 storage

sites are locally confined but might not necessarily store local emissions, it is very plausible that this type of fairness influences acceptance, too.

Another set of variables that seems promising but has received very little research attention are values, in particular what we call interference with nature – the belief that humans should not interfere with natural processes. Large perceived interference is associated with more negative attitudes. This concept was highly predictive of acceptance in studies by Wallquist et al. [20] and Tokushige et al. [19]. More research is needed to gain a clearer picture of what people perceive as interference with nature, and whether it is possible to change that perception, for example by pointing to natural analogues of underground gas storage. Perhaps CCS projects could be designed in a way that perception of interference is minimized. The exact role of these values for public perception could also be clarified.

Finally, increasing attention should be paid to dynamic processes that shape public perception. Understanding individual perceptions is of course important. Public perception of a technology, however, is not just the sum of individual perceptions, but the result of a dynamic process in which individuals and organizations interact. Particularly new technologies associated with certain risks and uncertainties can be subject to a social amplification of risk process [59,60]. The social amplification of risk framework (SARF) posits that risks are perceived and portrayed through risk signals; they can be images, signs or symbols. These signals are communicated among people, and each person or institution involved in this communication process will apply their own filters, heuristics and interpretations as they pass on the information. Thus, the perception of risks can be amplified or attenuated, as the information passes through the various "amplification stations." This can lead to so-called ripple effects that affect groups that were not originally involved with the risk event in question [60]. Kasperson et al. [59] gave the example of the Three Mile Island nuclear accident, which led to changes in management practices for nuclear power plants around the globe. If the CCS industry were confronted with a similar event that has a large signaling effect, such as a large-scale leak or a blowout at an injection well, this might tip public opinion of CCS and change which variables are the most predictive of acceptance.

7. Practical implications

In the previous section, we pointed out some research gaps that should be addressed. However, the existing body of research on public perception of CCS can also answer some important questions and allows certain conclusions for practitioners wanting to implement CCS.

Because CCS is such a new technology and very little known, one concern is often with informing the public. As mentioned in Section 6, we now have a fairly clear picture of what people's intuitive image of CCS is and which aspects are most important to correct. The majority of people accept climate change as real and relevant, which can be built on in communications. There seems to be considerable confusion, however, about the role of CO_2, where it comes from and which effects it can have, not just on the climate but also on human health. This should be explained in an introduction to CCS. Concerning the technology itself, widespread misconceptions revolve around geological storage mechanisms and the behavior of the CO2 in the reservoir. Communication materials should point out these misconceptions and then correct them.

It is certainly necessary to provide adequate and neutral information for the general public, and we would argue there is an ethical obligation to do so. But project developers should not overestimate the effect that such information materials have on acceptance. Even if people are motivated and able to process them carefully, the effect of knowledge on acceptance has been shown to be moderate at best. What is more influential is the context in which CCS is deployed: What other options for climate change mitigation are being pursued, who promotes CCS and why, how will costs and benefits generated by the technology be distributed, etc.

Most countries have no public participation processes for their national energy strategies or national laws governing the deployment of CCS. At the local level, however, when it comes to the implementation of specific CCS projects, the local population often has a say. If no formal engagement procedure is applied, they can at least organize local protests.

Case studies point to the importance of experience for acceptance of local CCS projects. The historical and social context of a potential host community should be carefully analyzed. If the local population has prior (positive) experience with the fossil fuel industry, they are more likely to be positively disposed to a CCS project. But even experiences that are not directly related to CCS may turn out to be relevant. If there have been other industrial activities in the past that had negative impacts on the community, this will shape people's reaction to a proposed CCS facility.

The latter point is related to aspects of fairness and trust. If people feel they have already been taken advantage of in the past and had to bear the negative consequences of industrial facilities, they will most likely not be willing to accept a CCS project. In a community that is neutral, perceived fairness can be enhanced by involving the local population as early as possible, giving them decision power wherever possible, and communicating openly and honestly. A problem that arises here is that project developers are typically energy companies. They are the least trusted stakeholder, and even honest communication might not achieve its goal. Therefore, it makes sense for project developers to seek cooperation with a more trusted stakeholder, such as a local citizen group or an NGO.

Local cooperation partners might also be able to help with the analysis of the local context and to identify local benefits for the community. This is an important issue. In studies about both societal acceptance and local acceptance, perceived benefits are crucial for acceptance. Their role is usually larger than that of perceived risks. The latter should not be disregarded, however. Perceived risks do have a significant impact on acceptance. They can to some extent be influenced by information, but they are also influenced by trust in stakeholders. What is important to bear in mind in the case of CCS is that one of the largest risks people see is the displacement of other efforts to mitigate climate change. This concern cannot be argued away with scientific findings. A prerequisite for acceptance of CCS in our view is that it is embedded in a solid energy strategy that people find acceptable.

To conclude, we would argue it is quite well understood which information is necessary to help people form their own opinion of CCS and make an informed decision. Project developers should pay attention to the local context of a proposed project site and focus on building an equal and trusted relationship with the local population.

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Appendix A

See Tables A1 and A2.

Table A1
Overview of the qualitative studies.

Study	Country	Method	Key findings
Anderson et al. [24]: "Exploring CCS community acceptance and public participation from a human and social capital perspective"	AU	Qualitative: interviews Sample: from affected communities	• Farmers had a closed social network and therefore closed information loop; proponent message thus reinforced • Farmers' acceptance declined during the project, but they remained passive and did not coordinate with their neighbors • Farmers would have been in need of capacity-building for human and social capital for a fairer and more transparent participation process
Ashworth et al. [25]: "What's in store: lessons from implementing CCS"	AU, NL, US	Qualitative: interviews about case studies Sample: stakeholders from each case	• Critical success factors for projects: alignment of government and development team; communication expert; consideration of social context and ability to adapt to changing social context • Components of effective stakeholder communication: timing (early); knowing the community; identifying local benefits; use of appropriate information channels
Ashworth et al. [46]: "Public acceptance of carbon dioxide capture and storage in a proposed demonstration area"	AU	Qualitative: workshops Sample: snowball sample from potentially affected communities	• Facilitated workshops are a useful engagement tool; perceived positively by participants • Main concerns: safety, leakage, groundwater contamination • Perceived benefits: employment and business opportunities, apart from climate change mitigation (which should not happen at the expense of renewables)
Fleishman et al. [31]: "Informed public preferences for electricity portfolios with CCS and other low-carbon technologies"	US	Qualitative: workshops with "homework" material Sample: from Greater Pittsburgh Metropolitan area, recruited through community organizations	• Participants favored energy efficiency over other low-carbon alternatives • Technologies with CCS preferred over their counterparts without CCS • Preferences were stable, rankings did not change after group discussions
Gough et al. [15]: "Burying carbon under the sea: an initial exploration of public opinions"	GB	Qualitative: focus groups Sample: convenience sample	• Problem perception: global warming seen as problem • Perceived risks/costs: high costs for an unsustainable solution, diversion of investment for renewable energy, infrastructure costs, leakage (in particular sudden and large), effects of seismic activity • Doubts that any institution can monitor stored CO_2 for centuries
L'Orange Seigo et al. [47]: "The effect of figures in CCS communication"	CH	Qualitative: interviews Sample: convenience sample	• Incorporation of mental models into illustrations of CCS does not aid comprehension • Suboptimal illustrations do not interfere with comprehension • Strong misconceptions cannot be corrected implicitly, by giving correct information; they need to be addressed explicitly
Oltra et al. [41]: "Lay perceptions of carbon capture and storage technology"	ES	Qualitative: focus groups Sample: quota sample from general population	• Dominant reaction in groups: rejection • Rejection driven by: perceived risks, preference for renewable energy technologies, perception that CCS does not contribute to solving climate change and energy problems • Perceived benefits very limited. If benefit from climate change mitigation seen as very high, then reluctant acceptance
Oltra et al. [26]: "Public responses to CO_2 storage sites: lessons from five European cases"	DE, PL, ES, NL	Qualitative: interviews, document analysis Sample: stakeholders (including public)	• No single factor can guarantee success or failure • Higher likelihood of positive community reaction if project: is at research scale; is managed by research organization; engagement strategy is proactive; trusted experts are involved; local benefits are seen; project is located in area with low population density with

Table A1 (*continued*)

Study	Country	Method	Key findings
			positive relationship with fossil fuel industry
Palmgren et al. [14]: "Initial public perceptions of deep geological and oceanic disposal of carbon dioxide" (Study 1)	US	Qualitative: interviews Sample: convenience sample	• Problem perception: most agree that global warming is problem • Perceived risks/costs: costs, efficacy, unforeseen negative consequences • Desire to consider CCS in broader set of options
Shackley et al. [48]: "The public perception of carbon dioxide capture and storage in the UK: results from focus groups and a survey"	GB	Qualitative (focus groups) and quantitative (interviews) Sample: from York and Manchester, skilled working class to middle class (focus groups); people at Liverpool airport (interviews)	• "Lukewarm" support; conditional on implementation of other options • Benefits: can mitigate climate change, buys time to develop other solutions • Perceived risks/costs: "Technical fix" that reduces incentives for other activities, blowouts
Upham and Roberts [27]: "Public perceptions of CCS: emergent themes in pan-European focus groups and implications for communications"	BE, DE, ES, GB, NL	Qualitative: focus groups Sample: "Representative of national populations" (unspecified)	• Knowledge/problem perception: people are concerned about climate change, low knowledge of CCS • More familiar energy technologies are taken as reference points – influenced by local context • Risk perception: 3 groups of risks: physical risks (especially leakage, supposed flammability of CO_2, seismicity), financial risks (cost seen as major disadvantage), governance risks • Trust: many trust neither government nor industry; scientists regarded as reliable information source • Perceptions across countries are very similar
Wallquist et al. [51]: "Lay concepts on CCS deployment in Switzerland based on qualitative interviews"	CH	Qualitative: interviews Sample: convenience sample	• Knowledge/problem perception: knowledge about CCS very low; agreement that climate change is a problem • Benefits: mitigate climate change • Perceived risks/costs: leakage (both slow and sudden blowouts); induced seismicity; diffuse harm to ecosystems; unsustainable technology; crowding out of renewable energy; rebound effect • CO_2 perceived as unhealthy and smelly
Wong-Parodi and Ray [28]: "Community perceptions of carbon sequestration: insights from California"	US	Qualitative: focus groups and interviews Sample: from potentially affected communities, one high status and one low status	• Primarily negative attitudes towards hosting CCS site • Perceived risks/costs: catastrophic leak; induced seismicity; technical risks might change nature of the town (e.g. property values) • Poorer community felt resigned and powerless • Sense of empowerment influenced by past experiences with industry-caused environmental damage
Wong-Parodi et al. [29]: "Influencing attitudes toward CCS. A social marketing approach"	US	Qualitative: interviews Sample: Snowballing, started with carefully identified "key informants" in 4 Wyoming communities	• Emotionally self-referent (ESR) triggers are the same for pro and anti CCS messages (but different "spin") • ESR triggers are the same across different subgroups, but their relative important changes • Citizens feel ESR messages should be coupled with expert messages

Table A2
Overview of the quantitative studies.

Study	Country	Method	Key findings
Carley et al. [52]: "Early public impressions of terrestrial carbon capture and storage in a coal-intensive state"	US	Quantitative: phone and mail survey Sample: random digit dialing with stratification Analysis: regression (probit)	• Knowledge: 80% have not heard of CCS • More positive view of CCS if respondent: believes human activities contribute to climate change, supports expanded use of low-carbon electricity sources, holds egalitarian worldview • More negative view of CCS if respondent: is a political conservative
de Best-Waldhober et al. [30]: "Informed and uninformed public opinions on CO_2 capture and storage technologies in the Netherlands"	NL	Quantitative: electronic survey, Information-Choice Questionnaire Samples: 2 representative samples Analysis: regression	• Knowledge: Most have very basic understanding of greenhouse gas effect (objective measures), but very low awareness of CCS technologies (subjective measures) • Half the respondents who had never heard of CCS gave evaluation anyway (pseudo-opinions); these opinions

Table A2 (*continued*)

Study	Country	Method	Key findings
			were unstable ● Informed respondents were somewhat positive towards CCS ● Aspects and consequences of technology could explain 35% of variance in evaluations of informed respondents
de Best Waldhober et al. [32]: "Public concepts of CCS: understanding the Dutch general public and its reflection in the media"	NL	Quantitative: electronic survey (informed by previous interviews) Sample: "similar to the Dutch population" (unspecified) Analysis: frequencies and ANOVA	● Many people unsure about characteristics, effects and sources of CO_2 ● Confusion about current energy production and its relation with climate change ● Effect of knowledge about CO_2 and CCS on attitude is small
de Best-Waldhober et al. [22]: "Informed public opinion in the Netherlands: evaluation of CO_2 capture and storage technologies in comparison with other CO_2 mitigation options"	NL	Quantitative: electronic survey, Information-Choice Questionnaire Sample: representative Analysis: frequencies and regression	● Informed participants evaluate CCS options not very favorably (below "acceptable" in Dutch school grading system) ● Despite this, large-scale implementation would be passively accepted by most people; does at least not spur protests ● Consequences of each electricity portfolio are relevant, but also leave much variance unexplained – other factors must influence people‘s judgments
Duan [21]: "The public perspective of carbon capture and storage for CO_2 emission reductions in China"	CN	Quantitative: interviews Sample: residents and visitors of Xiamen city Analysis: frequencies and regression	● Knowledge/problem perception: 24% had heard about CCS, high awareness of climate change ● Predictors of attitude: Sociodemographics not significant, CCS-related attitudes most important, benefit perception best predictor (66% explained variance)
Ha-Duong et al. [53]: "A survey on the public perception of CCS in France"	FR	Quantitative: interviews Sample: quota-based Analysis: frequencies	● Knowledge: High awareness of climate change mitigation options ● CCS not seen as overly effective, compared with other strategies ● Majority agrees with statement that CCS discourages development of renewable energy technologies ● Women are less accepting, but not more opposed (many "don't know" answers)
Huijts et al. [13]: "Social acceptance of carbon dioxide storage"	NL	Sample: from potentially affected communities (sampling method not specified) Analysis: frequencies and regression	● Knowledge: 76% know nothing or very little about CCS ● Risks rated higher than benefits; safety concerns ● Trust: Highest in environmental NGOs, lower in government, lowest in industry ● Trust predicted by perceived competence and perceived intentions; respective influence of each predictor depends on actor
Kraeusel and Möst [16]: "Carbon Capture and Storage on its way to large-scale deployment: Social acceptance and willingness to pay in Germany"	DE	Quantitative: conjoint study (+ survey) Sample: university students Analysis: regression and conjoint analysis	● Knowledge: High awareness, only 28% reported no/ little prior knowledge ● Risk and benefit perceptions can explain 77% of variance in acceptance, benefit perception more influential ● Factors conjoint study: Share of CCS power; share of green electricity; monthly price premium. Most important is increased share of green electricity ● Respondents who are more concerned about climate change perceive higher CCS-related risks
L'Orange Seigo et al. [33]: "Communication of CCS monitoring activities may not have a reassuring effect on the public"	CH	Quantitative: online experiment Sample: internet panel	● Information about CCS monitoring can be alarming ● Men‘s risk perception is heightened to the level of women, their acceptance is lowered
Midden and Huijts [37]: "The role of trust in the affective evaluation of novel risks: the case of CO_2 storage"	NL	Quantitative: survey Sample: random sample from potentially affected communities Analysis: structural equation modeling	● 2 factors found for affect: positive and negative ● Attitude towards nearby storage influenced only by affect, attitude towards storage in general more influenced by perceived benefits ● No effect of perceived risk on attitude ● Trust influenced perceived benefits but not risks; effect of trust on attitude via affect
Miller et al. [38]: "Public understanding of carbon sequestration in Australia: socio-demographic predictors of knowledge, engagement and trust"	AU	Quantitative: online survey Sample: commercial online panel Analysis: frequencies	● Women more likely to think that reducing greenhouse gas emissions is important, but less likely to have followed public debate

Table A2 (*continued*)

Study	Country	Method	Key findings
			• Men more accepting of CCS
Miller et al. [39]: "Initial public perceptions of carbon geosequestration: Implications for engagement and environmental risk communication strategies"	AU	Quantitative: online survey Sample: commercial online panel Analysis: frequencies	• Majority finds reduction of greenhouse gas emissions important; few, however, follow debate • Knowledge: Majority (82%) have not heard of CCS • Trust: Commonwealth Scientific and Industrial Research Organisation (CSIRO) trusted most, national government trusted least
Moutenet et al. [34]: "Public awareness and opinion on CCS in the province of Québec, Canada"	CA	Quantitative: online survey Sample: commercial online panel, weighted Analysis: frequencies	• Knowledge/problem perception: Climate change seen as important issue; CO_2 identified as greenhouse gas; green technologies well known, but CCS awareness at 13% • Only 8% fundamentally opposed • Opinion very sensitive to new information; after NGO views were presented, support declined substantially
Oltra et al. [35]: "The influence of information on individuals' reactions to CCS technologies: results from experimental online survey research"	ES	Quantitative: online experiment Sample: internet panel	• Participants who read information on the natural character of CO_2 have more positive initial reaction
Palmgren et al.[14]: "Initial public perceptions of deep geological and oceanic disposal of carbon dioxide" (Study 2)	US	Quantitative: survey Sample: convenience sample Analysis: frequencies	• CCS is least favored mitigation option; respondents want efficacy of storage better demonstrated • Possibility for continued use of fossil fuels not seen as compelling argument • Higher pro-environmental values associated with lower acceptance of CCS
Reiner et al. [54]: "American Exceptionalism? Similarities and differences in national attitudes toward energy policy and global warming"	GB, JP, SE, US	Quantitative: survey Samples: online panels and random samples Analysis: frequencies	• Knowledge/problem perception: Climate change recognized as problem; CCS mostly unknown • Similar preferences across countries for how national energy agencies should allocate funding • Information on cost & environmental impact of renewable energy technologies decreased support for renewable
Sharp et al. [23]: "Anticipating public attitudes toward underground CO_2 storage"	CA	Quantitative: online survey, conjoint study Sample: random digit dialing with quotas Analysis: conjoint analysis, regression	• Knowledge/problem perception: Agreement that climate change is a problem; low awareness of CCS • Respondents slightly supportive; influenced by extent to which CCS is used in other countries and media reports • Those opposed seem to be concerned about risks, rather than being fundamentally opposed
ter Mors et al. [40]: "Effective communication about complex environmental issues: perceived quality of information about CCS depends on stakeholder collaboration"	NL	Quantitative: experiments Samples: university students	• Information from different/dissimilar stakeholders expected to be more balanced than info from one single stakeholder • If a credible and a less credible stakeholder communicate together, their respective reputations are not affected
Terwel and Daamen [17]: "Initial public reactions to carbon capture and storage (CCS): differentiating general and local views"	NL	Quantitative: quasi-experiment Sample: general public convenience sample	• Initial reactions to local CCS plans not necessarily dominated by NIMBY sentiments • Onsite residents put greater emphasis on risks to local population • Trust in government indirectly affects attitude towards CCS, no effect of concern about climate change
Terwel et al. [44]: "It's not only about safety: Beliefs and attitudes of 811 local residents regarding a CCS project in Barendrecht"	NL	Quantitative: phone survey Sample: residents of Barendrecht Analysis: frequencies and regression	• Most residents were indeed opposed to the CCS project, and the issue was important for them • Predictors of attitude: Perceived safety of CO_2 storage, trust in decision makers, anticipated fall in property value, influence of Barendrecht residents, perceived fairness of decision-making process, influence of Shell
Terwel et al. [18]: "Competence-based and integrity-based trust as predictors of acceptance of carbon dioxide capture and storage (CCS)"	NL	Quantitative: experiments Samples: university students	• Stakeholder positions about CCS influence risk and benefit perceptions differently, depending on type of trust (integrity-based or competence-based) • Stakeholder position adopted when competence-based trust is high • Opposite position than that of stakeholder adopted when integrity-based trust is low

Table A2 (*continued*)

Study	Country	Method	Key findings
Terwel et al. [42]: "How organizational motives and communications affect public trust in organizations: the case of CCS"	NL	Quantitative: experiments Samples: university students	• Motives ascribed to a stakeholder mediate trust in that stakeholder • When stakeholder argues in favor of CCS, congruence between communication and inferred motives is predictive of trust, not message content alone
Terwel et al. [43]: "Voice in political decision-making: the effect of group voice on perceived trustworthiness of decision makers and subsequent acceptance of decisions"	NL	Quantitative: experiments Samples: university students	• Procedural information is used to judge trustworthiness of decision-makers; higher acceptance of outcome if decision-maker is trusted. • The mere presence of group voice affects reactions to authorities and their decisions, even when people are not involved themselves. • Equal treatment of different groups more important than giving specific groups a voice
Tokushige et al. [49]: "Public acceptance and risk-benefit perception of CO_2 geological storage for global warming mitigation in Japan"	JP	Quantitative: survey Sample: university students Analysis: factor analysis	• 92% of variance in attitude could be explained with risk and benefit perceptions • Benefit perception and acceptance increased after information provision, risk perception decreased somewhat • In comparison to nuclear power, CCS loads much lower on the dread factor and much higher on the unknown factor within the psychometric paradigm; additional information reduces dread dimension, but not unknown dimension
Tokushige et al. [49]: "Public perceptions on the acceptance of geological storage of CO_2 and information influencing the acceptance"	JP	Quantitative: survey Sample: university students Analysis: path analysis	• 83% explained variance in acceptance with risk perception, benefit perception, trust, perception of human interference with regard to global warming and with regard to CCS • Largest influence: benefit perception • Main concerns of people with high risk perception: leakage and earthquakes • Information on natural analogues decreased risk perception, increased acceptance; information on field demonstrations had little influence
Wallquist et al. [56]: "Public acceptance of CCS system elements: a conjoint measurement"	CH	Quantitative: conjoint study Sample: online panel of research group	• All 3 factors (plant, storage, pipeline) had main effect on acceptance • Pipeline most important, then plant, then storage • Participants could be clustered into 3 groups, each focusing on one aspect (plant/storage/pipeline) • NIMBY effect disappeared, if CO_2 source was a biogas power plant
Wallquist et al. [50]: "Adapting communication to the public's intuitive understanding of CCS"	CH	Quantitative: experiments Samples: respondents from a previous survey (mail survey experiment) and university students (lab experiment)	• Follow-up mail survey: more detailed information led to lower risk perception, higher benefit perception, lower sustainability concerns • Lab study: Information on reservoir pressure increased risk perception and decreased benefit perception; information on the liquid form of CO_2 in the reservoir and the role of CCS as a bridging technology decreased risk perception and increased benefit perception
Wallquist et al. [20]: "The role of convictions and trust for public protest potential in the case of carbon dioxide capture and storage (CCS)"	CH	Quantitative: survey Sample: random phone book sample Analysis: structural equation modeling	• Influence of risk perception on acceptance ("protest potential") larger than in other studies • "Tampering with the subsurface" best predictor for risk and benefit perception • Value conflict between "cutting emissions" and "tampering with the subsurface": both positively correlated, but opposite effects on benefit perception • Trust not significant for risk perception – perhaps because stakeholder positions are still unknown
Wallquist et al. [36]: "Impact of knowledge and misconceptions on benefit and risk perception of CCS"	CH	Quantitative: survey Sample: random phone book sample Analysis: regression	• Knowledge: 36% had heard of CCS, some misconceptions widespread • Risk perception: Strongest predictors are sustainability concerns, concerns about leakage and about reservoir overpressurization • Benefit perception: Sustainability concerns strongest predictor

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